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Final Report to TRMM
NAS5-32780

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The proposed effort consisted of three elements all having to do with the measurement of rain and clouds using microwaves. Briefly they were (1) to examine recently proposed techniques for measuring rainfall rate and rain water content using data from ground-based radars and the TRMM microwave link in order to develop improved ground validation and radar calibration techniques, (2) to develop dual-polarization, multiple frequency radar techniques for estimating the rain water content and cloud water content separately in order to better interpret the vertical profiles of Z measured by the TRMM Precipitation Radar and to develop a technique to measure quantities relevant to understanding the vertical distribution of latent heating by clouds and rain and (3) to investigate theoretically and experimentally the potential for biases in TRMM Precipitation Radar reflectivity factors (Z) because of spatial inhomogeneities in the precipitation. As explained below, all of these topics have been addressed and the associated research has led to several referred publications. These publications are listed at the end of this brief report, and copies of the cover papers are attached. Details (not repeated here) may be found in these articles.

As part of earlier TRMM research, several methods were developed for remotely estimating rain water content and rainfall rate using dual-polarization, multi-frequency microwave techniques (Jameson 1993; Jameson and Caylor 1994; Jameson 1994a; Jameson 1994b) using advanced polarization radars and microwave links. It was hoped that the TRMM microwave link would become operational, providing unique multi-frequency and dual-polarization microwave measurements in rain at the NASA Facility at Wallops Island, Virginia. That did not come to pass in the time frame of this proposal although the link is now undergoing final tests for such measurements. In lieu of these data, some measurements from the CaPE experiment in Florida in 1991 were processed and are included in the polarization component of an overview article "Evolution of Radar Rainfall Measurements: Steps and Mis-steps" co-authored with Dr. David

Atlas (Distinguished Scientist Emeritus, GSFC) and Prof. Daniel Rosenfeld (Hebrew University of Jerusalem). This publication appears as the lead article in a book just published by UNESCO as listed at the end of this report.

The factor limiting detailed study of these techniques was a lack of data. Proposals to NASA to acquire the necessary data primarily using NASA/JPL ARMAR radar were declined. Consequently, attempts were made to use some of the ARMAR aircraft observations. In general, however, these were not suited for this research because of the nearly nadir viewing angles in rain. However, in the course of exploring this data option, my colleague, Dr. Steven Durden at JPL, and I noticed the remarkable occurrence of linear depolarization even when looking down in rain. This led to the publication of an article co-authored with Steve Durden entitled "A Possible Origin of Linear Depolarization Observed at Vertical Incidence in Rain" that appeared in the *Journal of Applied Meteorology* in February 1996. Specifically, observations by two different nadir pointing airborne radars with some polarization capabilities have detected surprisingly large linear depolarization ratios at times in convective tropical rain. This depolarization can be explained if the rain is considered to be a mixture of a group of apparent spheres and another group of drops that are distorted in the horizontal plane perpendicular to the direction of propagation of the incident wave. If confirmed in future observations, this suggests that at times the larger raindrops are oscillating, in part, because of collisions with smaller drops. Since many of the interpretations of radar polarization measurements in rain by ground-based radars presume that the raindrops shapes correspond to those of the well-known, so-called 'equilibrium' drops, the present observations may require adjustments to some radar polarization algorithms for estimating rainfall rate, for example, if the shape perturbations observed at nadir also apply to measurements along other axes as well.

In addition, I worked with Dr. Ziad Haddad on research designed to help improve rainfall retrieval using the TRMM radar. This led to the publication of an article co-authored with Drs. Z. Haddad , E. Im and S.L. Durden (all of JPL) entitled "Improved Coupled Z-R and k-R Relations and the Resulting Ambiguities in the Determination of the Vertical Distribution of Rain from the Radar Backscatter and the Integrated Attenuation" that appeared in the *Journal of Applied Meteorology* in December 1995.

With regard to item (2) above, research led to the publication of an article entitled "Using Multiparameter Radars to Estimate the Attenuation and Water Content of Clouds" that appeared in the *Journal of Applied Meteorology*, September 1995. In summary it was reported that the attenuation of microwaves is caused not only by precipitation but also by clouds. Consequently, the presence of liquid cloud can affect estimates of rainfall rate computed from attenuation and reflectivity factors measured at higher frequencies typically used for spaceborne and airborne radars. Cloud attenuation also affects ground-based radar measurements of rainfall at frequencies as low as 5 GHz.

This paper suggests an approach for determining the attenuation due to cloud (A_C) and for estimating the cloud water content (W_C) even in moderate rain by using radars operating at two frequencies with one of them capable of dual-linear (horizontal-vertical) polarization measurements. This analysis suggests that useful 'instantaneous' estimates of A_C and W_C should be possible when an upper frequency of 13.8 GHz is used in conjunction with a lower frequency. These measurements could also be used to derive cloud attenuation statistics, potentially useful for developing techniques to help compensate for the effect of cloud attenuation on spaceborne, airborne and ground-based radar estimates of rainfall.

While this algorithm appears promising, it is particularly challenging to devise approaches to test this technique not only because the necessary instruments do not yet exist but also because of a lack of a standard for comparison. Although a complete test appears out of reach at this time, it should be possible at least to explore the validity of certain aspects of the technology. One possible approach using measurements over extended volumes is discussed at the end of this paper.

The final research topic led to some important insights regarding the structure of rainfall that is now being pursued in greater depth under new funding from the National Science Foundation. Specifically, research into this topic with Prof. A. B. Kostinski at Michigan Technological University led to an article entitled "Non-Rayleigh Signal Statistics Caused by Relative Motion during Measurements" that appeared in the *Journal of Applied Meteorology* in October 1996. It was reported that in order to reduce fluctuations, remote sensing devices such as radars and radiometers typically sample many times before forming an estimate. When mean values are stationary during this sampling period, the fluctuations in the amplitudes and intensities obey the same probability density functions (pdf's) as those for each sample contributing to the estimate. However, it is shown in this work that when mean values change from sample to sample (i.e., pulse to pulse for most radars), the pdf's of the amplitudes and intensities differ from those corresponding to the samples. Such changes can be inherent to the scatterers as, for example, the scatter of microwaves from an ocean surface, or they can be induced by factors such as antenna motion across gradients.

With respect to meteorological radars, it is routinely argued that the Central Limit Theorem leads inexorably to zero-mean Gaussian distributions of the two components of the electric field phasor backscattered from precipitation because of the large number of independent scatterers in the sampling volume. Consequently, the net amplitudes and intensities obey Rayleigh and exponential probability density distributions, respectively. While apparently true for each pulse (sample) even when the reflectivity across the beam is not uniform, we show that, in general, the underlying statistics of the amplitudes and intensities are no longer Rayleigh nor exponential. This occurs because the number of scatterers and intensities change from sample to sample as, for example, when a radar beam moves while the mean intensity is changing. Consequently, non-Rayleigh statistics and deviations from Gaussian distributions are probably much more common than previously appreciated.

A statistical model is developed and confirmed from detailed Monte Carlo drop simulations of a radar sampling as the beam moves through a cloud. Theory and these model simulations show that the resultant pdf's of the amplitude and intensity are mixtures of the pdf's from each sample contributing to the estimate. This mixture of pdf's also produces increased variance. Because of the general nature of these findings, it is likely that the effects of sampling through changing conditions (namely, biases and increased variances) probably also apply to many other types of remote sensing instruments including those using square law detectors. Fortunately, *this turns out not to be the case for the TRMM radar.* The reason is that the radar is steered electronically so that it uses what may be called 'block' averaging (Appendix) in which the beam is held stationary while each estimate is made. On the other hand, *the TRMM radiometers are not electronically steered and, therefore, may be subject to the non-Rayleigh effects described in this work.*

Aside from these important conclusions, attempts to advance this type of research led Prof. Kostinski and I to explore further the spatial (temporal) structure of rain. This led to the final paper entitled "Fluctuation Properties of

Precipitation. Part I: On Deviations of Single-Size Drop Counts from the Poisson Distribution" that appeared in the *Journal of the Atmospheric Sciences* on September 1997. Specifically, the traditional statistical description of the spatial and temporal distributions of cloud droplets and raindrops is the Poisson process that tends to place the drops as uniformly as randomness allows. Yet, the clumpy nature of clouds and precipitation is apparent to most casual observers. Is such clumpiness consistent with the Poisson statistics? Here we explore the possibility of deviations from the Poisson distribution using temporal raindrop counting experiments. Disdrometer measurements during the passage of a squall line strongly indicate that a mixture of Poisson distributions (Poisson mixture) provides a better description of the frequency of drop arrivals per unit time in variable rain than does a simple Poisson model. Poisson mixture generally yields distributions different from Poissonian. While the validity of the Poisson mixture model to smaller scales requires much finer temporal resolution than available in this study, these results do show that one must carefully interpret the statistical and physical meaning of average drop concentrations when the measurements are collected through variable rain, whether observed by airborne or ground-based instruments. Statistically, the variance in the measurements is greatly increased, due to the added variability from the rain field, thus minimizing the reduction of the variance normally achieved by increasing the sample size (N). In fact, in some cases the variance of relevant distributions scales as N^2 rather than N, thereby making the relative fluctuations independent of N. Consequently, the sampling criteria proposed by Cornford in 1967 are not necessarily generally applicable. Moreover, we conjecture that in most clouds the distribution of drop concentrations in small volumes may be more aptly described by a Poisson mixture rather than by a pure Poisson distribution. This may have significant implications with regard to the droplet growth and the evolution of rain. Already this research has led to new insights of obvious concern to TRMM into the meaning and measurement of drop size distributions in continuing research funded by the National Science Foundation and, therefore, not reported here.

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ATTACHMENTS

Atlas, D., D. Rosenfeld, and A.R. Jameson, 1997: Evolution of radar rainfall measurement: Steps and mis-steps. in Weather Radar Technology for Water Resources Management, **eds. B. Braga and O. Massambani, UNESCO Press, Montevideo, pp.1-60.**

EVOLUTION OF RADAR RAINFALL MEASUREMENTS: STEPS AND MIS-STEPS

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A Possible Origin of Linear Depolarization Observed at Vertical Incidence in Rain

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31 March 1995 and 17 August 1995

ABSTRACT

Recent observations by two different nadir-pointing airborne radars with some polarization capabilities have detected surprisingly large linear depolarization ratios at times in convective tropical rain. This depolarization can be explained if the rain is considered to be a mixture of a group of apparent spheres and another group of drops that are distorted in the horizontal plane perpendicular to the direction of propagation of the incident wave. If confirmed in future observations, this suggests that at times the larger raindrops are oscillating, in part, because of collisions with smaller drops. Since many of the interpretations of radar polarization measurements in rain by ground-based radars presume that the raindrop shapes correspond to those of the well-known "equilibrium" drops, the present observations may require adjustments to some radar polarization algorithms for estimating rainfall rate, for example, if the shape perturbations observed at nadir also apply to measurements along other axes as well.

1. Introduction

For many purposes including rainfall measurement using several recently developed radar polarization techniques, it is often assumed that raindrops are essentially quiescent, approximately oblate spheroids with their symmetry axes vertically oriented. Yet it is well known that drop size distributions evolve through the processes of coalescence, collision, and drop breakup, mechanisms likely to disturb such serenity. Presently, however, it is not known whether these perturbations are of sufficient magnitude to affect significantly the quantitative interpretation of radar polarization measurements. While an exploration of this latter question is beyond the scope of this article, as a first step we attempt to determine here whether possible drop perturbations are at least capable of producing effects detectable in the radar signals.

There are already hints that they do at times. For example, on occasion ground-based radars detect surprisingly large vertically polarized signals backscattered from rain even when the polarization of the incident wave is horizontal. At frequencies typical of most weather radars, perfectly quiescent, horizontally aligned raindrops are incapable of producing such depolarization, which requires dipole moments that are canted or tilted with respect to the polarization of the incident radar wave. Moreover, by using circular polarization radar measurements in rain, McCormick and Hendry (1974) found the mean "canting" angle (with respect to the plane of polarization) of the raindrops to be near zero but with a standard deviation of about 2°, consistent with the response of drops to turbulence (Beard and Jameson 1983). However, although this deviation is small, it is significant because the standard deviation of the instantaneous canting angle distribution should then be between 6° and 10° if the estimate of each mean is based upon between 9 and 25 independent radar samples. Calculations show that this would be sufficient to explain most values the cross-polarization in rain observed by radars viewing along a tangent to the ground. While such canting indicates that some fraction of the raindrop distribution is indeed agitated at times, it is not clear whether the processes producing the apparent canting also change the shapes of the drops as well.

In particular, suppose we observe rain using a nadir (downward) pointing radar. (In principle one could use an upward pointing radar, but then the measurements will be strongly affected by the wet radome and by

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Improved Coupled Z–R and k–R Relations and the Resulting Ambiguities in the Determination of the Vertical Distribution of Rain from the Radar Backscatter and the Integrated Attenuation

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ABSTRACT

Several algorithms to calculate a rain-rate profile from a single-frequency air- or spaceborne radar backscatter profile and a given path-integrated attenuation have been proposed. The accuracy of any such algorithm is limited by the ambiguities between the (multiple) exact solutions, which depend on the variability of the parameters in the Z–R and k–R relations used. In this study, coupled Z–R and k–R relations are derived based on the drop size distribution. It is then shown that, because of the coupling, the relative difference between the multiple mutually ambiguous rain-rate profiles solving the problem must remain acceptably low, provided the available path-integrated attenuation value is known to within 0.5 dB.

1. Introduction

The problem of estimating the vertical rain profile from measurements obtained using a single-frequency active air- or spaceborne radar, and subject to a path-integrated attenuation condition, has already been studied. Indeed, several algorithms have been proposed to find a "solution," that is, a rain-rate profile that does the job (see, e.g., Kozu and Nakamura 1991; Meneghini and Nakamura 1990; Weinman et al. 1990). However, even under ideal conditions where the measurements are perfectly calibrated, and in the absence of noise, the problem has multiple solutions. As shown in Haddad and Im (1993) and Haddad et al. (1995), this ambiguity is due to the fact that the parameters governing the classical power laws relating the radar reflectivity coefficient Z and the radar attenuation coefficient k to the rain rate R (or liquid water content W) depend on the drop size distribution. For example, in the Z–R relation $Z = aR^b$, empirical measurements have shown substantial variations in a and b. In fact, Battan (1973) reports over 70 Z–R relations due to differing drop size distributions. Without a path-integration constraint, rain retrieval requires assumed values for the parameters a, b, and the corresponding parameters in the k–R relation. Each combination of parameters provides a different solution. The path-attenuation constraint provides one additional equation relating the four parameters. However, without further constraints, because of the variability of these parameters, substantially different rain profiles can still be generated that produce the measured power profile and path-integrated attenuation (Haddad and Im 1993).

As was pointed out in Haddad et al. (1995), this ambiguity can be reduced if improved Z–R and k–R relations are used, specifically ones that do account realistically for the interdependence of the various parameters involved. In this paper, we derive such Z–R and k–R relations at Ku band using realistic scattering models and the results of Jameson (1993, 1994). The Ku band is of particular interest because it is the band of the Tropical Rainfall Measuring Mission's (TRMM) precipitation radar (Nakamura et al. 1990). We also derive the exact expressions for the mutually ambiguous rain profiles and show that while these multiple solutions are indeed mathematically different, the difference is relatively small if the path-integrated attenuation is known exactly. When the latter can be determined only to within a known uncertainty, we also show how our formulas produce bounds on the relative

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Using Multiparameter Radars to Estimate the Attenuation and Water Content of Clouds

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(Manuscript received 28 April 1994, in final form 14 March 1995)

ABSTRACT

The attenuation of microwaves is caused not only by precipitation but also by clouds. Consequently, the presence of liquid cloud can affect estimates of rainfall rate computed from attenuation and reflectivity factors measured at higher frequencies typically used for spaceborne and airborne radars. Cloud attenuation also affects ground-based radar measurements of rainfall at frequencies as low as 5 GHz.

This paper suggests an approach for determining the attenuation due to cloud (A_C) and for estimating the cloud water content (W_C) even in moderate rain by using radars operating at two frequencies with one of them capable of dual-linear (horizontal–vertical) polarization measurements. This analysis suggests that useful "instantaneous" estimates of A_C and W_C should be possible when an upper frequency of 13.8 GHz is used in conjunction with a lower frequency. These measurements could also be used to derive cloud attenuation statistics, potentially useful for developing techniques to help compensate for the effect of cloud attenuation on spaceborne, airborne, and ground-based radar estimates of rainfall.

While this algorithm appears promising, it is particularly challenging to devise approaches to test this technique, not only because the necessary instruments do not yet exist but also because of a lack of a standard for comparison. Although a complete test appears out of reach at this time, it should be possible at least to explore the validity of certain aspects of the technology. One possible approach using measurements over extended volumes is discussed at the end of this paper.

1. Introduction

As microwaves pass through clouds they are attenuated by the precipitation and cloud droplets. While usually of little concern at sufficiently low frequencies (e.g., $\leq$3 GHz), such attenuation can become appreciable at times at higher frequencies, thereby affecting the quantitative interpretation of radar measurements, for example. Even at a frequency as low as about 5 GHz, relations derived empirically from scatterplots of rainfall rate R versus radar reflectivity factor Z are biased by attenuation by rain and clouds (Atlas et al. 1993). While a distracting nuisance for some ground-based radars, it becomes a more critical problem likely to bias the estimates of the rainfall rates, particularly in the Tropics, using future spaceborne radars that must operate at frequencies greater than 10 GHz such as that for the Tropical Rainfall Measuring Mission (Simpson et al. 1988). While attempts are made to account for the effect of attenuation by rain using the measured height profiles of Z and estimates of the path total attenuation (Meneghini et al. 1983; Meneghini et al. 1989; Weinman et al. 1990; Haddad et al. 1995), the problem is further complicated because a significant fraction of the attenuation at times may be due to cloud rather than to rain. For example, when developing climatological Z–R relations for Darwin, Australia, Atlas et al. (1993) found that up to 25% of the attenuation at 5 GHz may be due to cloud. This is likely to be the case at higher frequencies as well. For example, Fig. 1 is a plot of the calculated ratio of the specific attenuation A_C of cloud (dB km^{-1}) to that for rain A_R in a "typical" thunderstorm (based upon Sekhon and Srivastava 1971) and for two different amounts of cloud water as well as for different radar frequencies ν. At frequencies below about 9 GHz, cloud water contributes significantly to the attenuation. While the attenuation contribution by cloud is relatively less important than by rain at higher frequencies, A_C is actually larger because it increases as ν^2. In this example (Fig. 1), as the cloud water content increases from 0.5 to 2 g m^{-3}, the contribution to the total attenuation by cloud increases from around 9% to about 30% for $\nu \geq 9$ GHz. Consequently, given sufficient cloud water there will actually be a large cloud attenuation signature at these frequencies provided the attenuation by rain can be estimated and subtracted from the total attenuation.

Aside from such practical attempts to improve radar rainfall estimates using higher frequencies, it is also of fundamental importance to measure cloud water. The spatial distribution of cloud water not only affects the radiation budget of the globe but is also crucial to the dynamics and thermodynamics of clouds and storms and for understanding precipitation formation and evolution. Yet it is not an easy quantity to measure,

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Non-Rayleigh Signal Statistics Caused by Relative Motion during Measurements

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(Manuscript received 5 July 1995, in final form 20 February 1996)

ABSTRACT

In order to reduce fluctuations, remote sensing devices such as radars and radiometers typically sample many times before forming an estimate. When mean values are stationary during this sampling period, the fluctuations in the amplitudes and intensities obey the same probability density functions (pdf) as those for each sample contributing to the estimate. However, it is shown in this work that when mean values change from sample to sample (i.e., pulse to pulse for most radars), the pdf's of the amplitudes and intensities differ from those corresponding to the samples. Such changes can be inherent to the scatterers as, for example, the scatter of microwaves from an ocean surface, or they can be induced by factors such as antenna motion across gradients.

With respect to meteorological radars, it is routinely argued that the central limit theorem leads inexorably to zero-mean Gaussian distributions of the two components of the electric field phasor backscattered from precipitation because of the large number of independent scatterers in the sampling volume. Consequently, the net amplitudes and intensities obey Rayleigh and exponential probability density distributions, respectively. While apparently true for each pulse (sample) even when the reflectivity across the beam is not uniform, the authors show that, in general, the underlying statistics of the amplitudes and intensities are no longer Rayleigh nor exponential. This occurs because the number of scatterers and intensities change from sample to sample as, for example, when a radar beam moves while the mean intensity is changing. Consequently, non-Rayleigh statistics and deviations from Gaussian distributions are probably much more common than previously appreciated.

A statistical model is developed and confirmed from detailed Monte Carlo drop simulations of a radar sampling as the beam moves through a cloud. Theory and these model simulations show that the resultant pdf's of the amplitude and intensity are mixtures of the pdf's from each sample contributing to the estimate. This mixture of pdf's also produces increased variance. Because of the general nature of these findings, it is likely that the effects of sampling through changing conditions (namely, biases and increased variances) probably also apply to many other types of remote sensing instruments including those using square-law detectors.

1. Introduction

The rapidly fluctuating intensities of radar echoes is one of the most noticeable characteristics of distributed meteorological targets such as precipitation. These fluctuations are the expression of constructive and destructive interference of waves scattered by each drop as they reshuffle because of different relative motions. While the basic physical understanding of coherent scatter has been known since the work of Rayleigh (1877) on the theory of sound, the application of this understanding to meteorological radar signal statistics gained general acceptance through the work of Marshall and Hitschfeld (1953).

Because the behavior of the amplitude of waves at a single frequency can be described in terms of a magnitude and a phase, it is often represented on a plane as a vector (referred to as a phasor) that moves in time. Associated with each position of the phasor there is also a projection of the X and Y components (also called the I and Q quadrature components in the literature) that fluctuate as the phasor moves. It is also well known that when there is a sufficient number of independent approximately equivalent scatterers and after adequate sampling, the central limit theorem leads to a zero-mean, equal variance, and uncorrelated Gaussian distributions of the X and Y components. As Marshall and Hitschfeld (1953) then show in the meteorological context, the Rayleigh probability distribution for the amplitude A and the corresponding resulting probability distribution of the intensity I ($=X^2 + Y^2$) follow and are given by

$$P(A)dA = \frac{2A}{\langle A^2 \rangle} \exp\left(\frac{-A^2}{\langle A^2 \rangle}\right) dA$$

$$P(I)dI = \frac{1}{\langle I \rangle} \exp\left(-\frac{I}{\langle I \rangle}\right) dI, \qquad (1)$$

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Fluctuation Properties of Precipitation. Part I: On Deviations of Single-Size Drop Counts from the Poisson Distribution

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(Manuscript received 13 September 1996, in final form 29 January 1997)

ABSTRACT

The traditional statistical description of the spatial and temporal distributions of cloud droplets and raindrops is the Poisson process, which tends to place the drops as uniformly as randomness allows. Yet, the "clumpy" nature of clouds and precipitation is apparent to most casual observers and well known to cloud physicists. Is such clumpiness consistent with the Poisson statistics? The authors explore the possibility of deviations from the Poisson distribution using temporal raindrop counting experiments. Disdrometer measurements during the passage of a squall line strongly indicate that a mixture of Poisson distributions (Poisson mixture) provides a better description of the frequency of drop arrivals per unit time in variable rain than does a simple Poisson model. Poisson mixture generally yields distributions different from Poissonian. While the validity of the Poisson mixture model to smaller scales requires much finer temporal resolution than available in this study, these results do show that one must carefully interpret the statistical and physical meaning of average drop concentrations when the measurements are collected through variable rain, whether observed by airborne or ground-based instruments. Statistically, the variance in the measurements is greatly increased, due to the added variability from the rain field, thus minimizing the reduction of the variance normally achieved by increasing the sample mean (N). In fact, in some cases the variance of relevant distributions scales as N^2 rather than N, thereby making the relative fluctuations independent of N. Consequently, the sampling criteria proposed by Cornford are not necessarily generally applicable. Moreover, the authors conjecture that in most clouds the distribution of drop concentrations in small volumes may be more aptly described by a Poisson mixture rather than by a pure Poisson distribution. This may have significant implications with regard to the droplet growth and the evolution of rain.

1. Introduction

The soothing sound produced by raindrops striking the roof of a house has long been considered a classic example of a Poisson process, that is, the probability of k drops arriving per unit time on a surface is described by the Poisson distribution (e.g., van Kampen 1992, 34). However, closer attention at times reveals hints of a rhythm in the rain. Presumably such pulsations have to do with "clumpiness" or "patchiness" often observed during a storm. While the structure of rain has been explored using radars (e.g., Crane 1990), such analyses have been restricted to spatial scales larger than about 1 km.

On scales much smaller than 1 km, it is usually assumed that raindrops and cloud droplets are nearly evenly distributed in space to the extent allowed by randomness. We quote from Rogers and Yau (1989, 134):

> Even in a well-mixed cloud with the same average droplet concentration throughout, there will be local variations in concentration. In particular, if n denotes the average concentration of droplets in a given size interval, then the number m of such droplets in a volume V obeys the Poisson probability law . . . .

Nevertheless, measurements in clouds often reveal complex structures in drop concentrations and cloud water contents. So what exactly, then, does "well mixed" mean?

To the extent that turbulence is responsible for stirring, clumpiness is to be expected because turbulence is well known to be intermittent and spotty. That is, an initially homogeneous "blob" of cloud droplets (assumed sufficiently light to be regarded as passive tracers) will be twisted and distorted by a succession of turbulent eddies as time progresses. The resultant

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15. Supplementary Notes

16. Abstract

The effort involved three elements all related to the measurement of rain and clouds using microwaves:

(1) Examine recently proposed techniques for measuring rainfall rate and rain water content using data from ground-based radars and the TRMM microwave link in order to develop improved ground validation and radar calibration techniques;
(2) Develop dual-polarization, multiple frequency radar techniques for estimating rain water content and cloud water content to interpret the vertical profiles of radar reflectivity factors (Z) measured by the TRMM Precipitation Radar; and
(3) Investigate theoretically and experimentally the potential biases in TRMM Z measurements due to spatial inhomogeneities in precipitation.

The research succeeded in addressing all of these topics, resulting in several refereed publications. In addition, the research indicated that the effects of non-Rayleigh statistics resulting from the nature of the precipitation inhomogeneities will probably not result in serious errors for the TRMM radar measurements, but the TRMM radiometers may be subject to significant bias due to the inhomogeneities.

17. Key Words (Suggested by Author(s))

radar	polarization
rain	dual-polarization radar
microwave	latent heating
ground truth	radar reflectivity factors
TRMM	spatial inhomogeneities

18. Distribution Statement
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